

Collisional perturbation of states in atomic ytterbium by helium and neon

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Results of an investigation of collisional deexcitation of the metastable $6s6p\ ^3P_0$ state in atomic ytterbium by helium and neon buffer gases are reported. We find upper limits for the quenching cross sections to be $\sigma_{\text{He}} < 13 \times 10^{-22} \text{ cm}^2$ and $\sigma_{\text{Ne}} < 8 \times 10^{-22} \text{ cm}^2$. The small cross sections may allow an ytterbium parity nonconservation experiment to be performed in a vapor cell. We have also measured the pressure broadening and shift of the $6s6p\ ^3P_0 \rightarrow 6s7s\ ^3S_1$ and $6s^2\ ^1S_0 \rightarrow 6s6p\ ^3P_1$ transitions by helium and neon.
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I. INTRODUCTION

The $6s^2\ ^1S_0 \rightarrow 6s5d\ ^3D_1$ transition in atomic ytterbium (Yb) was recently proposed as a candidate for the study of parity nonconservation (PNC) [1] (hereafter the upper and lower states of this transition will be referred to as 1S_0 and 3D_1 , respectively). This transition is well suited for the PNC Stark interference technique, with a relatively large predicted PNC-induced $E1$ amplitude ($E1_{\text{PNC}} \approx 10^{-9} e a_0$ [1–3]), a moderate Stark-induced $E1$ amplitude (vector transition polarizability $|\beta| = 2.18(33) \times 10^{-8} e a_0 / (\text{V/cm})$ [4]) and a small $M1$ amplitude [5]. Many of the Yb atoms (approximately 70% [6]) excited to the 3D_1 state subsequently decay to the metastable $6s6p\ ^3P_0$ state (hereafter referred to as 3P_0 , Fig. 1). Since one-photon radiative decays from the 3P_0 state to the ground state are strictly forbidden by the $J=0 \leftrightarrow J'=0$ selection rule, the lifetime of the metastable state is limited primarily by collisional deexcitation (quenching). Thus, if the quenching rate is sufficiently small, an effective detection scheme for an Yb PNC experiment is possible by inferring the $^1S_0 \rightarrow ^3D_1$ transition rate from the population of atoms which accumulate in the 3P_0 state. This population can be efficiently probed by measuring absorption of laser light tuned to the 649 nm $^3P_0 \rightarrow 6s7s\ ^3S_1$ (hereafter 3S_1) transition. This technique may enable an Yb PNC measurement to be performed in a vapor cell, offering a potential improvement in statistical sensitivity to PNC effects compared to an experiment performed with an atomic beam.

In a vapor-cell experiment, it is desirable to employ buffer gas to limit diffusion of Yb atoms from the probe region. At sufficiently high buffer-gas pressures, relatively large electric fields can be applied without breakdown, which is convenient for observing the Stark-induced $^1S_0 \rightarrow ^3D_1$ transition. The optimal shot-noise-limited signal-to-noise ratio in a measurement of the 3P_0 population by absorption of 649-nm light is achieved with two absorption lengths at 649 nm [7]. If the 3P_0 quenching rate and pressure broadening of the 649-nm probe transition are sufficiently small, it is possible to build up a large population of absorbing atoms, allowing efficient detection of atoms having made the $^1S_0 \rightarrow ^3D_1$ transition.

In the present experiment, quenching cross sections of the 3P_0 state and pressure broadening and shift of the 649 nm $^3P_0 \rightarrow ^3S_1$ transition with respect to helium (He) and neon (Ne) are measured. The 3P_0 state is populated by exciting Yb atoms from the ground state to the $6s7p\ ^3P_1$ state with a pump laser light pulse (Fig. 2) followed by a cascade decay. The population of the 3P_0 state is continuously monitored by measuring the absorption of probe laser light at 649 nm. The quenching rate is determined from the time dependence of the 3P_0 population. Measurements of the quenching rates at various buffer-gas pressures and Yb densities yield upper limits on the 3P_0 quenching cross sections. The line shape of the 649-nm transition in the vapor cell is obtained by measuring absorption as a function of probe beam frequency. In order to determine the pressure broadening and shift of the $^3P_0 \rightarrow ^3S_1$ transition, the absorption profile is compared to a reference line observed by optogalvanic spectroscopy.

There have been a number of previous studies of depolarizing and elastic cross sections of the $6s6p\ ^3P_1$ (hereafter 3P_1) state [12–16], but the pressure broadening and shift of the 556-nm $^1S_0 \rightarrow ^3P_1$ transition is measured here for the first time to our knowledge. Frequency calibration is performed by comparing absorption profiles in the vapor cell with fluorescence data from an Yb atomic beam.

In this paper, we first describe the experimental setup for measurement of quenching cross sections of the 3P_0 state and pressure broadening and shift of the 649-nm $^3P_0 \rightarrow ^3S_1$ transition in Sec. II A. In Sec. II B, we describe the setup for measuring the pressure broadening and shift of the 556-nm $^1S_0 \rightarrow ^3P_1$ transition. In Sec. III we discuss the dependence of the absorption profile on various experimental parameters. The results are presented in Sec. IV. Finally, in Sec. V we consider the implications of these measurements for an ytterbium parity nonconservation experiment.

II. EXPERIMENTAL SETUP

A. 3P_0 quenching cross sections and $^3P_0 \rightarrow ^3S_1$ pressure broadening and shift

The experimental apparatus for measuring the 3P_0 collisional quenching cross sections and 649-nm $^3P_0 \rightarrow ^3S_1$ pres-

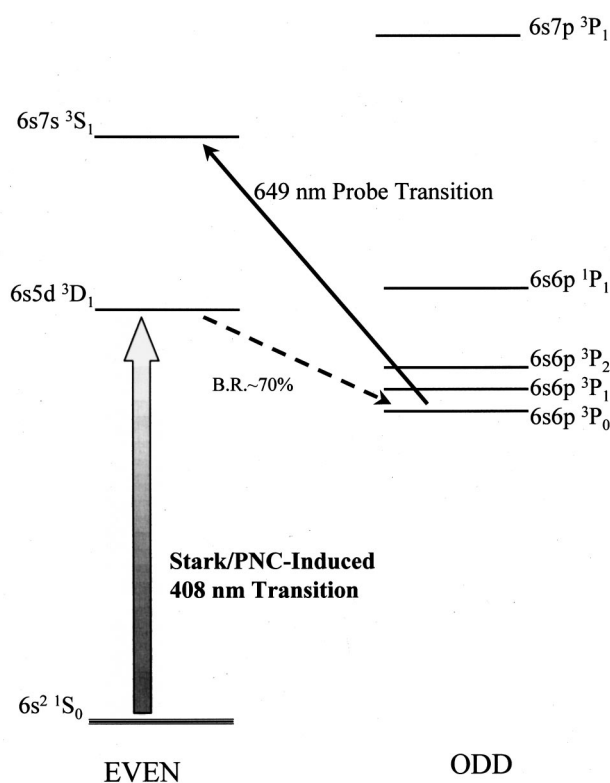


FIG. 1. Partial energy-level diagram of atomic ytterbium and relevant transitions for the proposed PNC experiment in a vapor cell.

sure broadening and shift is shown schematically in Fig. 3. A few grams of Yb (natural isotopic abundance) are placed in the center of a resistively heated, tantalum-lined stainless-steel vapor cell. Before measurements are performed, the vapor cell is pumped down to $\sim 10^{-2}$ Torr with a mechanical vacuum pump and baked overnight at 500 K to remove impurities. In order to reduce the introduction of impurities into the cell, gas lines in and out of the vapor cell pass through a liquid-nitrogen trap. A trap filled with steel wool is in line between the mechanical pump and the vapor cell to prevent cell contamination with vacuum pump oil.

Cross-section and pressure broadening and shift measurements were performed at a temperature of 700 ± 10 K in the central region of the vapor cell (the middle 20 cm heated by a ceramic beaded heater [17]). The temperature of the central

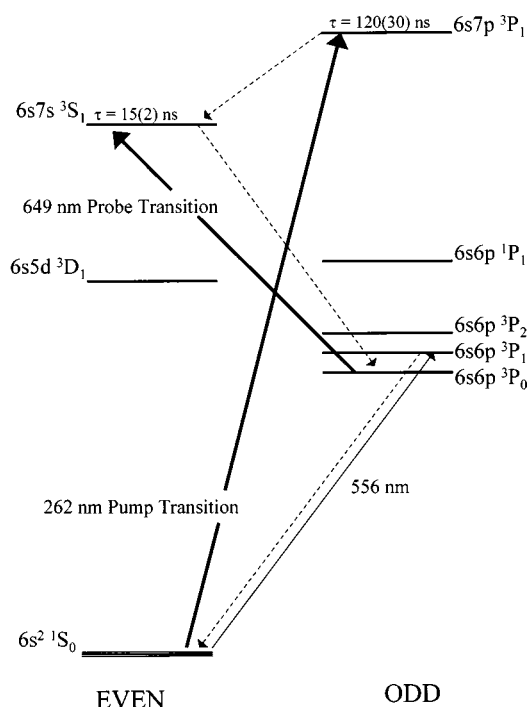


FIG. 2. Partial energy-level diagram of atomic ytterbium and relevant transitions for quenching cross section and pressure broadening and shift measurements. The lifetime of the $6s7s\ ^3S_1$ state is from Refs. [8–10], and the lifetime of the $6s7p\ ^3P_1$ state is from Ref. [11].

region measured with a thermocouple is consistent with that deduced from the observed Doppler width of Yb resonance lines. For some data sets, the Yb density is monitored by observing the absorption of 556-nm light tuned near the $^1S_0 \rightarrow ^3P_1$ transition. The Yb density is in agreement with the predicted saturated vapor pressure [18], corresponding to an average Yb density of $\sim 5 \times 10^{12}$ atoms/cm³ in the central region. The column length of ytterbium vapor is approximately 20 cm, roughly matching the length of the heated central region of the vapor cell. Buffer-gas pressure in the vapor cell is monitored by two capacitance manometers (MKS Baratron) with ranges of 100 and 5000 Torr.

The pulsed 262-nm pump beam is produced by an excimer (Lambda Physik EMG 101 MSC) pumped dye laser (Lambda Physik FL 2002) with frequency doubling. Coumarin 521 dye generates light at 524 nm. The 524-nm light

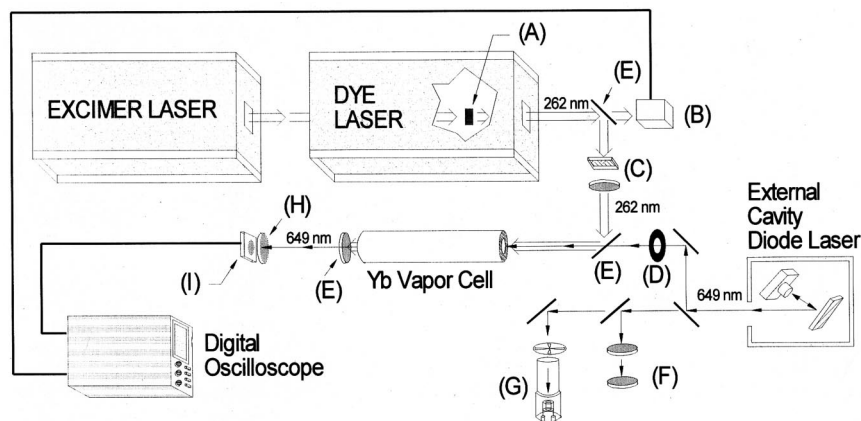


FIG. 3. Experimental setup for the Yb $6s6p\ ^3P_0$ collisional de-excitation cross section and 649-nm $6s6p\ ^3P_0 \rightarrow 6s7s\ ^3S_1$ pressure broadening and shift measurements: (A) BBO crystal; (B) fast photodiode trigger; (C) UV filter and lens to expand 262-nm beam diameter; (D) iris; (E) dichroic mirror; (F) confocal scanning Fabry-Perot; (G) Yb hollow cathode lamp; (H) 650-nm interference filter; and (I) photodiode.

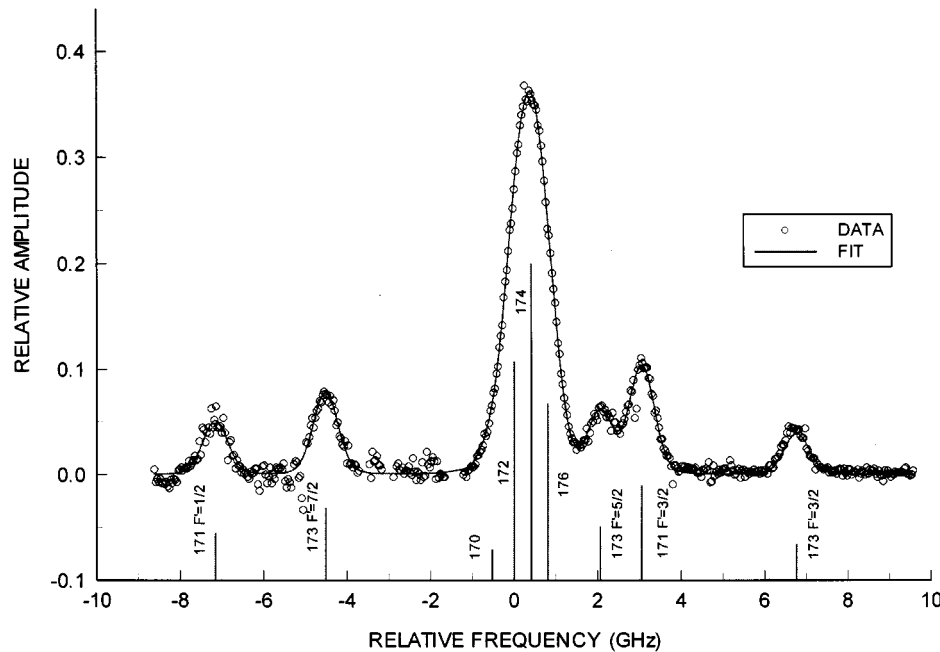


FIG. 4. Optogalvanic spectrum of the 649-nm $^3P_0 \rightarrow ^3S_1$ transition. Our results for the isotope shifts and hyperfine structure agree with previous measurements [21–23]. Isotopic components are labeled with the respective atomic masses, and F' is the total angular momentum of the upper state of a hyperfine transition.

passes through a beta barium borate (BBO) crystal to produce second-harmonic light at 262 nm. The laser system operates with a repetition rate of 5 Hz, and each pulse at 262 nm has an energy of ≈ 0.5 mJ, a duration of ≈ 20 ns, and a spectral width of ≈ 0.5 cm^{-1} . A lens expands the 262-nm beam diameter to ≈ 1 cm in the central interaction region of the vapor cell. The 262-nm pump beam has a broad spectral width, so all isotopic and hyperfine components of the $6s7p$ 3P_1 state, and consequently the 3P_0 state, are populated. The pump beam spectral width is larger than the Doppler width, so velocity changing collisions do not affect the probe signal. The pump beam typically transfers 5–10% of the ground-state population to the 3P_0 state.

The 649-nm probe beam is generated by a homemade external cavity diode laser system [19]. The single-frequency output is typically 10 mW, tunable over approximately 3–5 GHz without mode hops or multimode behavior. The spectrum of the diode laser is monitored with a confocal scanning Fabry-Perot interferometer.

Most of the probe laser output is directed into a commercial Yb hollow cathode lamp [20] filled with neon buffer gas. We use the optogalvanic signal from the hollow cathode lamp to tune the probe laser to resonance with the $^3P_0 \rightarrow ^3S_1$ transition [7]. The spectrum of the $^3P_0 \rightarrow ^3S_1$ transition measured with optogalvanic spectroscopy is shown in Fig. 4.

The probe beam diameter is reduced to ≈ 1 mm before entering the vapor cell, and its power is attenuated to < 1 μW . We find that at this laser intensity the probe beam does not significantly affect the population of the metastable 3P_0 state compared to other loss mechanisms, in agreement with estimates of optical pumping rates [7].

The probe and pump beams are aligned collinearly on the axis of the vapor cell, with the smaller probe beam centered inside the larger pump beam. This geometry ensures that at sufficient buffer-gas pressures, atoms in the metastable 3P_0 state diffuse out of the pump region more slowly than they are quenched by collisions (i.e., the quenching rate signifi-

cantly exceeds the diffusion rate $\Gamma_{\text{quench}} \gg \Gamma_D$). We verify experimentally that slight misalignment of the beams has no discernible effect on measurements.

The 262-nm beam is retroreflected by a dichroic mirror as it exits the cell, while the 649-nm light is transmitted. The probe beam intensity after passing through the cell is measured with a photodiode fitted with a 650-nm central wavelength interference filter with a 10-nm bandwidth.

B. Pressure broadening and shift of the $^1S_0 \rightarrow ^3P_1$ transition

The pressure broadening and shift of the 556-nm $^1S_0 \rightarrow ^3P_1$ transition is determined by comparing the absorption spectrum in the vapor cell to fluorescence from an Yb atomic beam. Light at 556 nm is generated by a ring dye laser (Spectra-Physics 380D, using Rhodamine 110) pumped by an Ar^+ laser (for these measurements, the pulsed 262-nm pump beam is absent). The atomic beam apparatus is essentially the same as that used in our previous work, described in detail in Ref. [4]. Light at 556 nm excites atoms in the atomic beam to the 3P_1 state and fluorescence at 556 nm is detected with a photomultiplier tube. A portion of the laser output is coupled into a single-mode optical fiber which takes the light into a different laboratory where measurements with the vapor cell are performed. Photodiodes monitor the intensity of incident light before and after passing through the cell. The power of the light passing through the vapor cell is attenuated to less than 500 nW, far below saturation of the transition. The laser is scanned over 20 GHz for line-shape measurements. For high Yb densities and buffer-gas pressures—when the lines in the vapor cell are broad—it is necessary to concatenate multiple scans to determine both the shape of the wings and the position of the line center. Frequency markers from Fabry-Perot interferometers and isotope shifts and hyperfine structure of the $^1S_0 \rightarrow ^3P_1$ transition allow us independent ways to calibrate the frequency scans of the laser.

III. DEPENDENCE OF THE ABSORPTION PROFILE ON EXPERIMENTAL PARAMETERS

The intensity of light $I(\omega, t)$ transmitted through the ytterbium vapor cell is described by

$$I(\omega, t) = I_0(\omega) e^{-\alpha(\omega, t)l}, \quad (1)$$

where $I_0(\omega)$ is the light intensity before entering the vapor cell, l is the column length of the Yb vapor, and $\alpha(\omega, t)$ is the absorption coefficient, given by

$$\alpha(\omega, t) = \frac{3\pi c^2 n(t)}{\omega_0^3 \tau} \frac{\omega}{\gamma_D} V(\omega) = \alpha(\omega, 0) \frac{n(t)}{n(0)}, \quad (2)$$

where $n(t)$ is the density of Yb atoms in the lower state of a given transition within the probe region at time t , ω_0 is the resonant frequency of the transition, ω is the frequency of the probe laser, τ is the upper-state lifetime [$\tau = 15(2)$ ns for the 3S_1 state [8–10], and $\tau = 872(2)$ ns for the 3P_1 state [24]], γ_D is the Doppler width, and $V(\omega)$ is the Voigt line-shape function [$V(\omega)$ includes relative intensities of hyperfine components and isotopic abundance]. Self-broadening [which could mimic a change in 3P_0 population by causing $V(\omega)$ to acquire a time dependence] was found to be insignificant [7]. Thus a measurement of the intensity of light transmitted through the vapor cell directly determines the density of Yb atoms in the 3P_0 state as a function of time.

Yb atoms in the 3P_0 state are lost from the probe region by diffusion and quenching by buffer-gas atoms, Yb atoms (both in the ground state and excited states), and possible gaseous impurities. Measurements of 3P_0 loss rates with respect to 262-nm pump beam power and Yb density indicate that quenching cross sections for ground- and excited-state Yb atoms are roughly the same ($\sigma_{Yb} \sim 10^{-14} \text{ cm}^2$) [7]. Branching ratio estimates indicate that ~ 70 – 80% of Yb atoms are in the ground state ~ 200 ns after excitation by the 262-nm pump pulse. Therefore we assume Yb-Yb quenching is primarily due to atoms in the ground state, and include contributions from excited-state quenching in our uncertainties.

The diffusion rate of Yb atoms in the 3P_0 state from the probe region decreases as the buffer-gas density is increased, while collisional quenching rates increase with the perturber density. Therefore, it is straightforward to distinguish collisional quenching from any losses due to diffusion. Data are taken at sufficiently high buffer-gas pressure (≥ 100 Torr) where losses by diffusion are negligible.

Since we operate in the regime of low buffer-gas density ($\sigma^{1/2} < n^{-1/3}$), we consider only two-body collisions in the impact approximation [25]. The time dependence of the population of the $6s6p \ ^3P_0$ state is given by

$$\frac{dn}{dt} \cong -\Gamma n \cong -(\Gamma_B + \Gamma_{Yb} + \Gamma_I)n, \quad (3)$$

where n is the density of Yb atoms in the 3P_0 state, Γ is the total 3P_0 Yb loss rate from the probe region, and Γ_B , Γ_{Yb} , and Γ_I are the quenching rates due to collisions with buffer-gas atoms, ground-state Yb atoms, and residual gaseous impurities, respectively. Therefore,

$$n(t) = n(0) e^{-\Gamma t}, \quad (4)$$

where $n(0) \approx 10^{11} \text{ cm}^{-3}$ is the initial density of Yb atoms in the 3P_0 state just after excitation by the 262-nm pump pulse. Under typical experimental conditions, the sum of the quenching rates due to Yb atoms and/or possible gaseous impurities is ~ 300 – 500 s^{-1} , as determined from loss rates extrapolated to zero buffer-gas pressure. The quenching rate with respect to the buffer gas Γ_B depends linearly on the buffer-gas density n_B :

$$\Gamma_B = n_B \sigma_B \bar{v}_{\text{rel}}, \quad (5)$$

where σ_B is the quenching cross section for this process, and

$$\bar{v}_{\text{rel}} = \left(\frac{8k_B T}{\pi \mu} \right)^{1/2} \quad (6)$$

is the average relative velocity between colliding Yb atoms and buffer-gas atoms, μ is the reduced mass of the Yb–buffer-gas atom system, k_B is Boltzmann's constant, and T is the temperature. If ytterbium and impurity densities in the vapor cell are independent of buffer gas pressure, so are Γ_{Yb} and Γ_I .

The normalized Voigt line-shape function $V(\omega)$ in Eq. (2) is given by [26]

$$V(\omega) = \sum_j C_j g(z_j(\omega)), \quad (7)$$

where the index j refers to various isotopic and hyperfine components, the C_j 's are constants which account for the isotopic abundance and the relative intensity of particular hyperfine components, and

$$g(z_j(\omega)) = \text{Re}\{\sqrt{\pi} \exp[-z_j(\omega)^2] (1 - \Phi[-iz_j(\omega)])\}. \quad (8)$$

Here $\Phi[x]$ is the complex error function [27], and

$$z_j(\omega) = \frac{\omega - \omega_j}{\gamma_D} + i \left(\frac{\gamma_N + \gamma_P}{2\gamma_D} \right), \quad (9)$$

where ω_j is the resonance frequency of a particular isotopic or hyperfine component, γ_N is the natural width, and γ_P is the pressure width. The determination of the absorption coefficient as a function of probe laser detuning allows us to extract both the Doppler and pressure widths. We use previously measured values for the separation of hyperfine and isotope components in our fits [21–23, 28–30]. We assume the same broadening and shift for all hyperfine components.

IV. RESULTS AND DISCUSSION

A. 3P_0 quenching cross sections

Yb atoms excited from the ground state to the $6s7p \ ^3P_1$ state by the 262-nm pump beam populate the 3P_0 state via cascade decay within about 150 ns. Once the 3P_0 state is populated, the medium is no longer transparent to the 649-nm probe beam [Eqs. (1) and (2)]. The photodiode detector circuit which monitors probe beam intensity after passing through the cell has a finite response time of $\tau_r \approx 50 \mu\text{sec}$. At times t much longer than τ_r the voltage signal

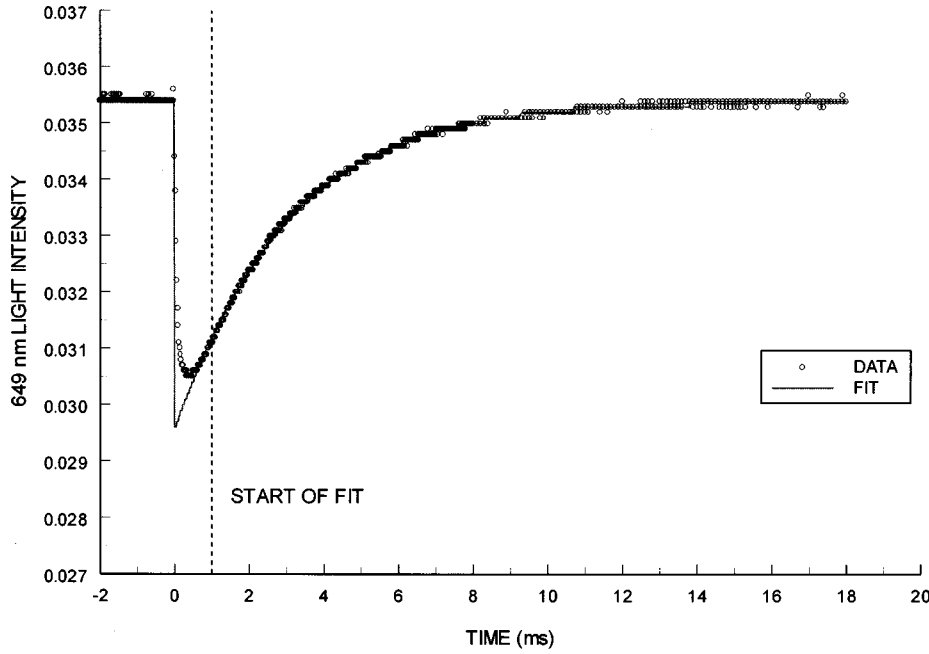


FIG. 5. Intensity of 649-nm light transmitted through the vapor cell. This particular data set is with neon buffer gas at a pressure of 100 Torr. The 262-nm pulse passes through the vapor cell at $t=0$, populating the $6s6p\ ^3P_0$ state. The fit is performed with data after $t=1$ ms, where the photodiode circuit response effects have died away.

$\varphi(t)$ from the photodiode is given by an approximation to a convolution of the detector response function with the input signal [7]:

$$\varphi(t) = A_0 \exp[-\alpha(\omega, 0)l \exp[-\Gamma t]], \quad (10)$$

where A_0 is an amplitude factor proportional to the incident light intensity. For each pulse the experimental signal is saved to computer and fit by Eq. (10). Analysis yields values for the total loss rate Γ and the absorption coefficient $\alpha(\omega, 0)$. A typical fit is shown in Fig. 5.

Data are taken at buffer-gas pressures ranging from 100 to 600 Torr. At higher pressures, collisional broadening of the probe transition reduces the signal-to-noise ratio to less than 1. Below approximately 100 Torr, diffusion dominates over quenching. Figure 6 shows the total loss rate Γ with respect to He and Ne densities.

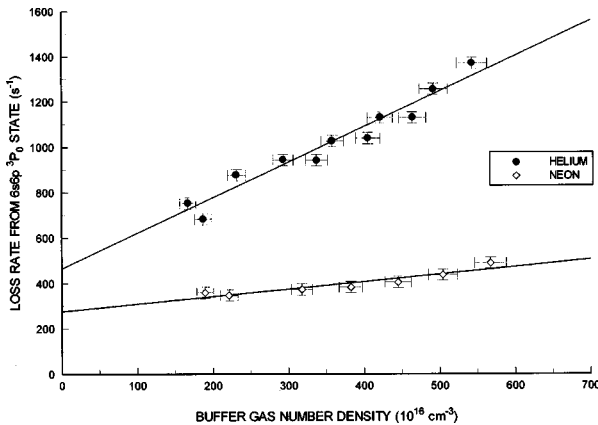


FIG. 6. Total loss rate Γ of Yb atoms in the $6s6p\ ^3P_0$ state from the probe region with respect to the buffer-gas density. Each data point is the average of 4–8 laser pulses. The straight lines are least-squares fits. The difference between the y intercepts of the two data sets is consistent with changes in 3P_0 loss rates due to variations in ytterbium density between runs.

The quenching cross sections with respect to He and Ne are small ($\sigma_B \leq 10^{-21} \text{ cm}^2$). Therefore, although our observations are consistent with quenching by buffer-gas atoms, it is possible that a slight dependence of Yb or impurity density on buffer-gas pressure could account for the linear dependence of Γ on buffer-gas density seen in Fig. 6. For this reason, we interpret our results as an upper limit for the 3P_0 quenching rate due to collisions with buffer-gas atoms [Eq. (5)]. Sources of uncertainty in the measurements of quenching rates at different buffer-gas pressures and their contribution to the uncertainty in σ_B are summarized in Table I, briefly explained below and considered in more detail in Ref. [7].

Measurement of Yb density variations with respect to buffer-gas pressure at fixed cell temperature provides a limit on the uncertainty in σ_B from quenching by Yb atoms, $\delta(\sigma_B)_{Yb}$,

$$\delta(\sigma_B)_{Yb} \leq \frac{\Delta n_{Yb}}{\Delta n_B} \frac{\bar{v}_{rel}(Yb-Yb)}{\bar{v}_{rel}(Yb-B)} \sigma_{Yb}, \quad (11)$$

where Δn_{Yb} is the upper limit on change in Yb density for a given change in buffer-gas density Δn_B . Although the measurements for He and Ne were performed near the same vapor cell temperature (700 K), the total Yb density probably

TABLE I. Sources of uncertainty in determination of σ_B in units of 10^{-22} cm^2 .

Source of uncertainty	Helium	Neon
Variation of Yb density	1.0	1.9
Quenching by excited-state Yb	2.5	2.5
Uncertainty in buffer-gas density	0.7	0.3
Change in Γ with start time of fit	4.1	1.2
Statistical	0.5	0.4
Total	5.0	3.5

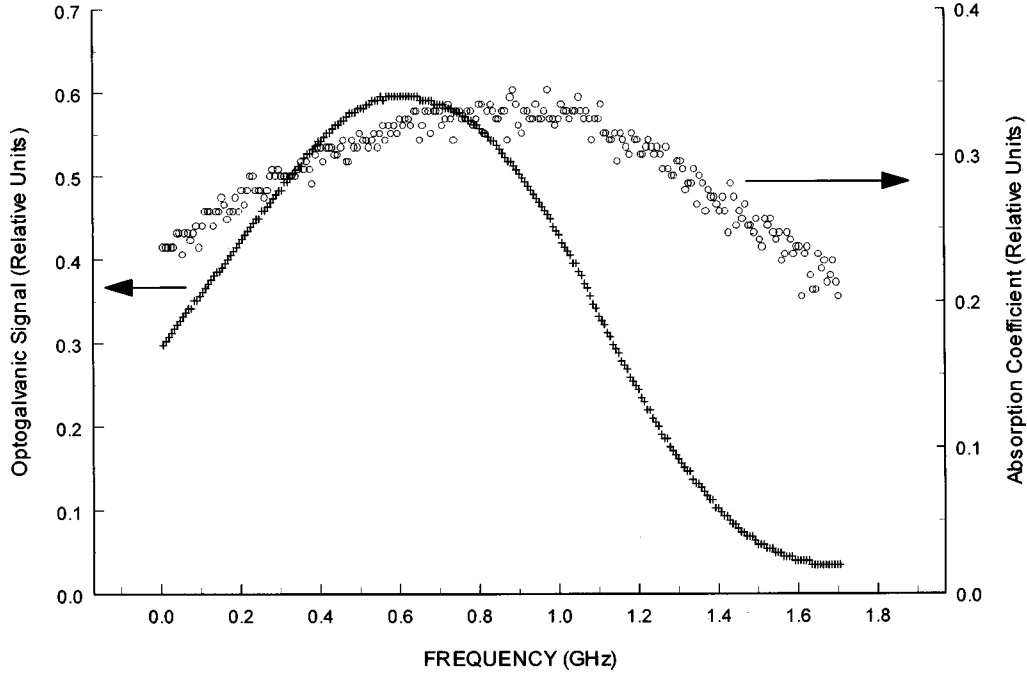


FIG. 7. Typical data for measurement of pressure broadening and shift of the 649-nm $6s6p\ ^3P_0 \rightarrow 6s7s\ ^3S_1$ transition. This data set focuses on the even isotope components (see Fig. 4) at a helium pressure of 70 Torr.

differed between runs. A relatively small difference in cell temperature between runs (10 K) leads to a substantial difference in Yb density (30%) [18]. This may account for the difference between extrapolated quenching rates at zero buffer-gas pressure for He and Ne in Fig. 6 (Yb density was not monitored directly in these experimental runs).

Quenching by excited-state Yb atoms also introduces a systematic uncertainty. As buffer-gas density changes, relative populations of ground- and excited-state Yb atoms may change. The contribution of this uncertainty to σ_B is constrained by Yb density measurements and estimates of excited-state quenching cross sections [7].

Since the cell is pumped down to 10^{-2} Torr, it is possible that the impurity density in the cell could be as large as 10^{14} cm^{-3} . In principle, impurity density may be proportional to buffer-gas density, so gaseous impurities in the cell can add to the measured value of σ_B .

The buffer-gas density was deduced from the measured pressure and temperature in the interaction region. Hence, uncertainties in buffer-gas pressure and cell temperature lead to an uncertainty in buffer-gas density.

An additional systematic uncertainty arises from a slight dependence of the deduced value of Γ on the start time of the fit, indicating that Eq. (10) is not a perfect description of our data. This discrepancy may be attributed to quenching by Yb atoms in excited states or a nonuniform Yb density distribution within the probe region [7]. These effects can lead to a more complicated time dependence of the transmitted light intensity than assumed in Eq. (10). The change in the quenching rate with the start of the fit is relatively small ($\sim 5\%$), so we include it as an uncertainty in the cross-section values. Considering these uncertainties, we find that $\sigma_{\text{He}} < 13 \times 10^{-22}\text{ cm}^2$ and $\sigma_{\text{Ne}} < 8 \times 10^{-22}\text{ cm}^2$.

B. Pressure broadening and shift of the $^3P_0 \rightarrow ^3S_1$ transition

Varying the frequency of the 649-nm probe light allows us to determine the line shape of the $^3P_0 \rightarrow ^3S_1$ transition at various buffer-gas pressures. The intensity of 649-nm light transmitted through the vapor cell is measured at a fixed time after the pump pulse populates the 3P_0 state. We fit the data to Eq. (1) using the frequency dependent absorption coefficient [Eq. (2)], and extract the pressure width from the normalized Voigt profile [Eqs. (7)–(9)]. Comparison with the simultaneously recorded optogalvanic signal from the Yb hollow cathode lamp allows us to determine the relative pressure shift. Typical data are shown in Fig. 7. The Doppler width is determined by fits to data near zero buffer-gas pressure, and is in agreement with the observed temperature in the central region of the vapor cell. Fits to a Voigt profile with the Doppler width held constant determine the width due to collisional broadening. Pressure shift and width at various He and Ne pressures are plotted in Fig. 8, and the results for the pressure broadening and shift of the $^3P_0 \rightarrow ^3S_1$ transition are given in Table II. Systematic uncertainties due to laser frequency scan nonlinearity and uncertainties in the vapor-cell temperature and buffer-gas pressure were found to be on the order of the statistical spread of the points. Possible gaseous impurities in the cell do not significantly affect these measurements, since buffer-gas-induced broadening and shift cross sections are of the usual size (10^{-15} – 10^{-14} cm^2), and the impurity density is relatively low.

C. Pressure broadening and shift of the $^1S_0 \rightarrow ^3P_1$ transition

The intensity of the 556-nm light transmitted through the vapor cell is also described by Eq. (1), but in this case the

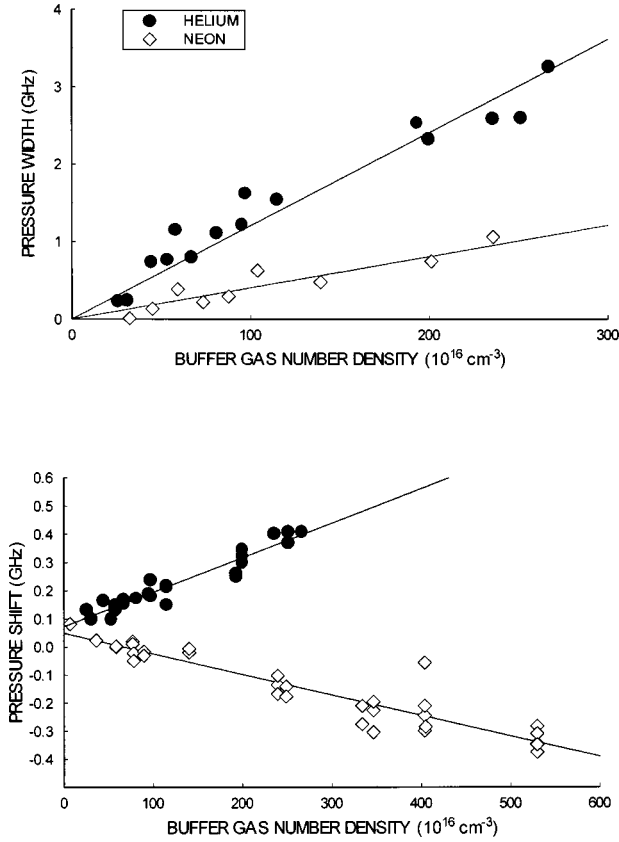


FIG. 8. Pressure broadening and shift of the 649-nm $6s6p\ ^3P_0 \rightarrow 6s7s\ ^3S_1$ transition by helium and neon.

absorption coefficient is time independent. Pressure broadening of the $^1S_0 \rightarrow ^3P_1$ transition is found from fits to the 556-nm absorption profile [Eqs. (1) and (2) and (7)–(9)]. The pressure shift is determined by comparing the 556-nm fluorescence from the atomic beam to absorption in the vapor cell (Fig. 9). Figure 10 shows a plot of the pressure broadening as a function of He and Ne number densities. The results are presented in Table II. The scatter of shift data is relatively large due to the difficulty in absolute frequency calibration of the featureless absorption profile at high buffer-gas density. Least-squares fits give shifts consistent with zero for both He and Ne.

V. CONSEQUENCES FOR A PARITY NONCONSERVATION EXPERIMENT

The exceptionally small collisional de-excitation cross sections of the 3P_0 state may make an Yb PNC experiment in a vapor cell advantageous. A possible configuration for such an experiment is shown in Fig. 11. Here the PNC observable is a difference in transition rates arising from the

interference of Stark-induced and PNC-induced transition amplitudes for right- and left-handed experimental configurations. This geometry is similar to that of the PNC experiment performed with cesium by the group in Boulder [31]. The asymmetry corresponding to the pseudoscalar rotational invariant $\vec{\sigma} \cdot (\vec{E} \times \vec{B})$ would be measured by comparing how many Yb atoms are excited to the upper state of the 408-nm $^1S_0 \rightarrow ^3D_1$ transition for different orientations of $\vec{\sigma}$ (angular momentum of excitation photons), \vec{E} (static electric field), and \vec{B} (static magnetic field).

In an envisioned PNC experiment, Yb atoms will be excited to the 3D_1 state by 408-nm light produced by directing continuous-wave laser light into a multipass cavity or a power buildup cavity. Most of the atoms excited to the 3D_1 state subsequently decay to the 3P_0 state. As in the present work, the 3P_0 population will be monitored with a weak probe beam at 649 nm (Fig. 1). Performing a parity violation measurement in a vapor cell offers a number of potential advantages compared to a similar experiment in an atomic beam. A vapor cell enables higher counting rates due to greater atomic density and volume in the probe region, and greater detection efficiency is achieved by measuring absorption of a probe laser as opposed to measuring fluorescence. Optimization of the experimental conditions for a PNC experiment in a cell will depend on parameters which are not currently known (e.g., the $^1S_0 \rightarrow ^3D_1$ pressure broadening). Here we point out that with plausible conditions (similar to those used in this work, where possible), a vapor-cell PNC experiment with Yb indeed appears to give improved sensitivity compared to a beam experiment.

We conservatively estimate that the cavity inside the vapor cell should be able to achieve a gain of 500 (about two orders of magnitude less than that achieved by the Boulder group [31], due to the use of a vapor cell rather than an atomic beam). With an input power of ≈ 200 mW, this is sufficient to produce approximately 100 W of power at 408 nm in the interaction region. Two absorption lengths at the probe transition requires a density of $\sim 10^{10}$ Yb atoms per cm^3 in the 3P_0 state (for a 50-cm-long interaction region). After pumping for a sufficiently long time ($> \Gamma_{\text{pump}}^{-1}$),

$$n_{3P_0} = \frac{\Gamma_{\text{pump}}}{\Gamma_{\text{loss}}} n_{\text{total}}, \quad (12)$$

where the pumping rate Γ_{pump} (in s^{-1} , assuming a beam diameter of ≈ 1 mm), is given by

$$\Gamma_{\text{pump}} \approx \frac{(|\beta| E_{\text{stat}} E_{408})^2}{\gamma_R}, \quad (13)$$

TABLE II. Pressure broadening and shift rates (Γ/n) in units of $10^{-9} \text{ s}^{-1} \text{ cm}^3$.

Transition	Helium		Neon	
	Broadening	Shift	Broadening	Shift
649-nm $6s6p\ ^3P_0 \rightarrow 6s7s\ ^3S_1$	7.5 ± 1.3	0.8 ± 0.1	2.5 ± 0.3	-0.5 ± 0.1
556-nm $6s^2\ ^1S_0 \rightarrow 6s6p\ ^3P_1$	3.8 ± 0.1	0.0 ± 0.5	1.5 ± 0.1	-0.5 ± 1.0

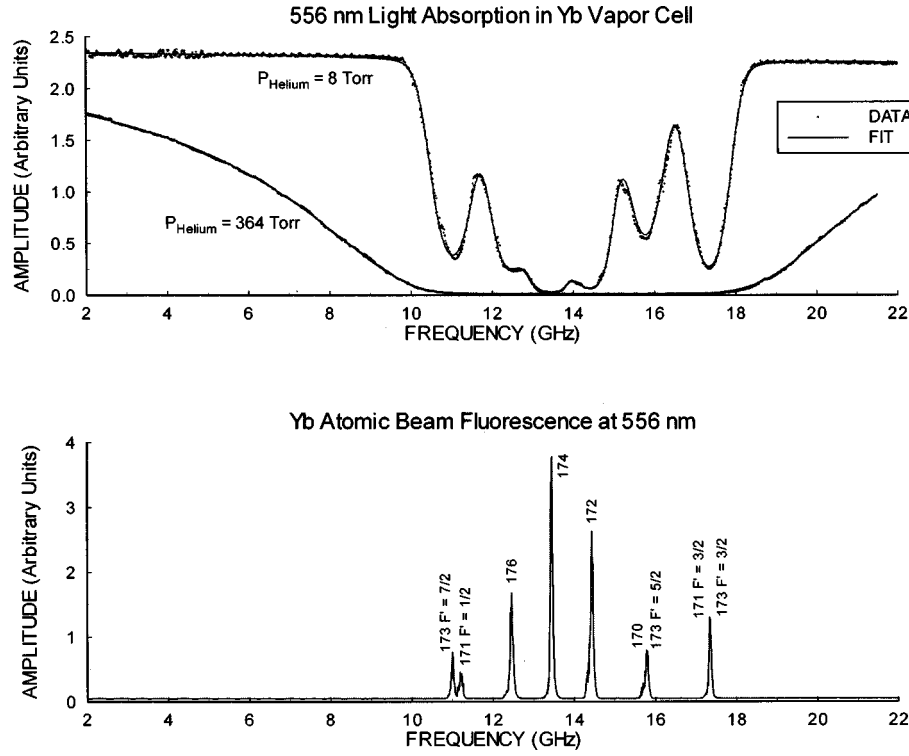


FIG. 9. Typical data for measurement of the pressure broadening and shift of the 556-nm $6s^2 \ ^1S_0 \rightarrow 6s6p \ ^3P_1$ transition. For atomic beam fluorescence data, isotopic components are labeled with the respective atomic masses, and F' is the total angular momentum of the upper state of a hyperfine transition.

where E_{stat} is the static electric field, E_{408} is the electric field amplitude of the 408-nm light, and γ_R is the larger of either the Doppler or pressure widths (depending on cell conditions). For example, using neon as the buffer gas at a pressure of $\approx 400 \text{ Torr}$ and at a cell temperature of $\approx 700 \text{ K}$ (yielding a total Yb density of $5 \times 10^{12} \text{ atoms/cm}^3$), the necessary static electric field is $\approx 900 \text{ V/cm}$. For an electric-field plate separation of 1 cm the breakdown voltage for neon under these conditions is $\approx 1750 \text{ V/cm}$ [32], so such a field amplitude is probably achievable in the proposed experimental configuration.

The fractional uncertainty in a measurement of $E1_{\text{PNC}}$ can be estimated to be

$$\left(\frac{\delta E1_{\text{PNC}}}{E1_{\text{PNC}}} \right)^2 \approx \frac{N_{\text{total}}}{(\Delta N_{\text{PNC}})^2}, \quad (14)$$

where N_{total} is the total number of atoms detected in the 3P_0 state,

$$N_{\text{total}} \approx \frac{(|\beta| E_{\text{stat}} E_{408})^2}{\gamma_R} N_{\text{Yb}} T \epsilon_d, \quad (15)$$

and ΔN_{PNC} is the difference in the total number of atoms detected in the 3P_0 state between different \vec{E}_{stat} orientations (the asymmetry due to PNC Stark interference), given by

$$\Delta N_{\text{PNC}} \approx \frac{4|\beta| E_{\text{stat}} E1_{\text{PNC}} E_{408}^2}{\gamma_R} N_{\text{Yb}} T \epsilon_d, \quad (16)$$

where $E1_{\text{PNC}}$ is the PNC-induced $E1$ amplitude for the 408-nm transition, N_{Yb} is the total number of Yb atoms in

the interaction region, T is the measurement time in seconds, and ϵ_d is the detection efficiency. This yields an uncertainty in $E1_{\text{PNC}}$ of

$$(\delta E1_{\text{PNC}})^2 \approx \frac{1}{T} \left(\frac{\gamma_R}{16 E_{408}^2 N_{\text{Yb}} \epsilon_d} \right). \quad (17)$$

As is commonly the case in Stark PNC interference experiments, there is no dependence on the static electric field [33].

We can now compare the statistical sensitivity of such an Yb PNC experiment performed in a vapor cell to a similar experiment in an Yb atomic beam. Based on estimates of experimental parameters from this work for a vapor cell and from Refs. [1, 4, 5] for an atomic beam (presented in Table

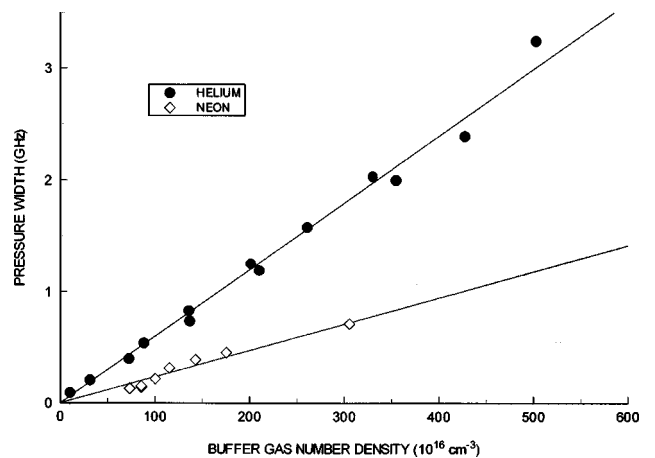


FIG. 10. Pressure broadening of the 556-nm $6s^2 \ ^1S_0 \rightarrow 6s6p \ ^3P_1$ transition.

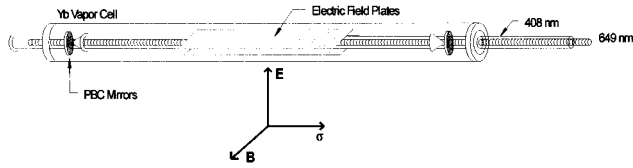


FIG. 11. Schematic diagram of the apparatus for a proposed Yb PNC experiment in a vapor cell.

III), from Eq. (17) we find the fractional uncertainties in $E1_{\text{PNC}}$ for a cell experiment and a beam experiment to be

$$\left(\frac{\delta E1_{\text{PNC}}}{E1_{\text{PNC}}} \right)_{\text{cell}}^2 \approx \frac{5 \times 10^{-6}}{T},$$

$$\left(\frac{\delta E_{\text{PNC}}}{E1_{\text{PNC}}} \right)_{\text{beam}}^2 \approx \frac{10^{-4}}{T}.$$

This demonstrates that an Yb vapor-cell experiment may offer advantages in statistical sensitivity to PNC effects in comparison to an atomic beam experiment.

However, there remain a number of issues that need to be addressed before pursuing an Yb PNC experiment in a vapor cell. These include collisional broadening of the 408-nm $^1S_0 \rightarrow ^3D_1$ transition, ionization of Yb atoms by the 408-nm light, and collisionally assisted transition rates to the 3D_1 state. These questions will be addressed in future experimental work.

VI. CONCLUSION

We have placed upper limits on the collisional quenching cross sections of the $6s6p\ ^3P_0$ metastable state in atomic ytterbium with respect to helium and neon. The cross sections are sufficiently small so that quenching is not a limiting factor for the proposed Yb PNC cell experiment. In addition, we have measured the pressure broadening and shift of the

TABLE III. Estimated experimental parameters for Yb PNC experiment in a vapor cell and an atomic beam.

Parameter	Cell	Beam
E_{408}	3 kV/cm	12 kV/cm
γ_R	$2\pi \times 1000$ MHz (pressure width)	$2\pi \times 30$ MHz (Doppler width)
ϵ_d	1	0.1
N_{Yb}	2.5×10^{11} atoms	2×10^8 atoms

$6s6p\ ^3P_0 \rightarrow 6s7s\ ^3S_1$ and $6s^2\ ^1S_0 \rightarrow 6s6p\ ^3P_1$ transitions. Future work will involve the construction of a new vapor cell with electric-field plates. This new apparatus will allow us to further investigate the feasibility of an Yb PNC experiment in a vapor cell. In order to obtain values for the quenching cross sections of the $6s6p\ ^3P_0$ metastable state improved vacuum, gas handling, and heating systems will be employed. This will further eliminate gaseous impurities and allow better control of the Yb density.

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